In-Flight Observations of Long-Term Single-Event Effect (SEE) Performance on Orbview-2 Solid State Recorders (SSR)

Christian Poivey, *Member, IEEE,* Janet L. Barth, *Senior Member, IEEE*, Kenneth A. LaBel, *Member, IEEE,* George Gee, and Harvey Safren

***Abstract*--We present multi-year Single Event Upset (SEU) flight data on Solid State Recorder (SSR) memories for the NASA Orbview-2 mission. Actual SEU rates are compared to the predicted rates based on ground test data and environment models.**

I. Introduction

THIS paper presents Single Event Effect (SEE) in-flight data on Solid State Recorders (SSR) that have been collected over a long period of time for the Orbview-2 NASA spacecraft. SEE flight data on solid-state memories give an opportunity to study the behavior in space of SEE sensitive commercial memory devices. The actual Single Event Upset (SEU) rates can be compared with the calculated rates based on environment models and ground test data. The SEE mitigation schemes can also be evaluated in actual implementation. A significant amount of data has already been published concerning observed SEE effects on memories in space [1-18]. However, most of the data presented cover either a short period of time or a small number of devices. The data presented here have been collected on a large number of devices for a 4.3-year period. This allows statistically significant information about the effect of space environment fluctuations (space weather) on SEU rates, and the effectiveness of SEE countermeasures used to be analyzed.

Manuscript received July 18, 2003. This work was supported by the NASA Electronic Parts and Packaging (NEPP) program's Electronics Radiation Characterization (ERC) project and Defense Threat Reduction Agency (DTRA).

C. Poivey is with SGT-Inc., Greenbelt, MD 20771 USA (telephone: 301-286-2128, e-mail: cpoivey@pop500.gsfc.nasa.gov).

J. L. Barth, is with NASA-GSFC, Greenbelt, MD 20771 USA (telephone: 301-286-8046, e-mail: janet.l.barth@nasa.gov).

K. A. LaBel, is with NASA-GSFC, Greenbelt, MD 20771 USA (telephone: 301-286-9936, e-mail: Kenneth.a.Label@nasa.gov).

G. Gee, is with SGT-Inc., Greenbelt, MD 20771 USA (telephone: 301-286-8595, e-mail: ggee@pop900.gsfc.nasa.gov).

H. Safren is with NASA-GSFC, Greenbelt, MD 20771 USA (telephone: 301-286-5507, e-mail: harvey.g.safren.l@gsfc.nasa.gov).

II. Mission and SSR Description

The Orbview-2 spacecraft carries the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) instrument. SeaWiFS provides quantitative data on global ocean bio-optical properties to the Earth science community. Orbview-2 was launched in August 1997 into a circular, 705 km altitude, 98 degrees inclination, sun-synchronous orbit.

Orbview-2 carries two SSRs. Each SSR is capable of storing up to 512 Mbit of science data while awaiting relay to Earth. Each SSR contains 880 Mbit of memory (704 Mbit usable). Each SSR is organized as 40 Mword (32 Mword usable) of 22 bits size (16 bits of data, 6 bits of code). The SEU mitigation scheme is the Hamming Error and Detection And Correction Code (EDAC). The Hamming EDAC code is capable of correcting a single bit error in a word, and detecting a double bit error. In addition to EDAC, the memories are kept free from the accumulation of SEUs by a scrubbing. Each memory word is regularly read, corrected, and written back in turn every 16 minutes. The SEU information is gathered by telemetry at 10 second intervals. These SSRs, designed and built by SEAKR, use 4Mx1 Dynamic Random Access Memories (DRAM) MDM1400G-120 from MOSAIC/HITACHI. Each SSR contains 220 DRAMs.

III. In-Flight Data

Orbview-2 SEU data have been collected from January 1, 1999, to April 6, 2003. As shown in Fig. 1, this period corresponds to the peak of the maximum phase of the current solar cycle.

Fig. 2 shows the daily upset counts for both SSRs. We can see a day-to-day variation of +/-30%. Significantly higher upset counts were observed on July 14 and 15, 2000, November 9, 2000, April 15, 2001, September 25, 2001 November 4, 5, and 6, 2001, April 21, 2002, and August 24, 2002. These high upset counts correspond to the largest Solar Particle Events (SPEs) observed during this solar cycle and are well correlated with the increased solar protons fluxes as measured by the GOES spacecraft [20].

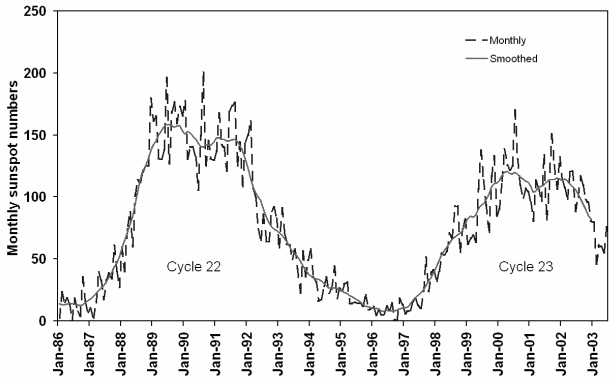

Fig. 1. Monthly sunspot numbers for the past 17 years [19].

We can also see in Fig. 2 a general decrease of the upset counts with time. This decrease is more visible in Fig. 3 that shows the monthly averages of the daily upset numbers. In the beginning of January 1999, the average SEU count per day was about 255; during the first months of 2003, the average SEU count per day was about 170. This decrease is consistent with lower trapped proton and Galactic Cosmic Ray (GCR) fluxes that correspond to the increasing solar activity.

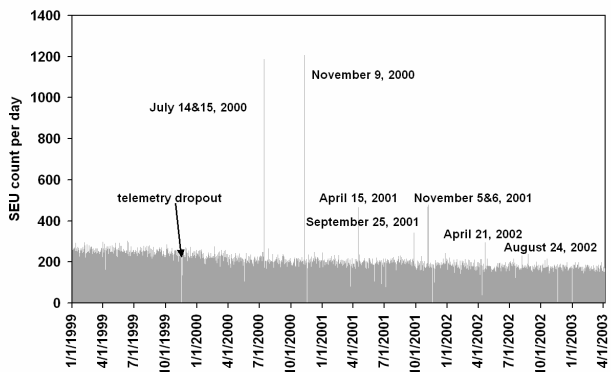

Fig. 2. Daily SEU counts for both Orbview-2 SSRs from January 1, 1999 to April 6, 2003.

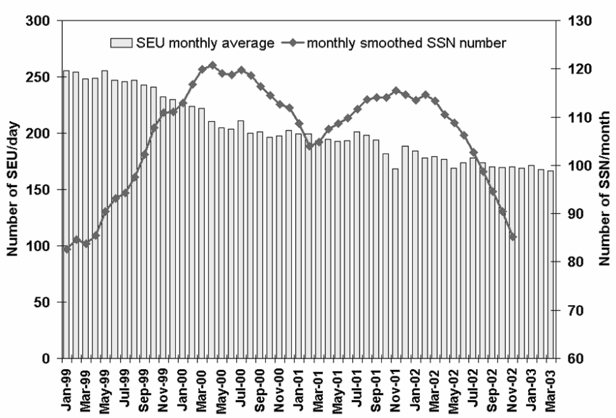

Fig. 3. Monthly averages of SEU counts for both Orbview-2 SSRs and number of sunspots [19] from January 1, 1999 to April 6, 2003.

Fig. 4 shows the cartography of SEUs for a typical day, July 13, 2000. On this day the SEU count was 225. More than 85% of the SEUs occured from proton exposure within the South Atlantic Anomaly (SAA) where the spacecraft spends less than 20% of its orbit time. The other upsets are spread over the high latitude regions of the orbit where the spacecraft encounters background GCRs.

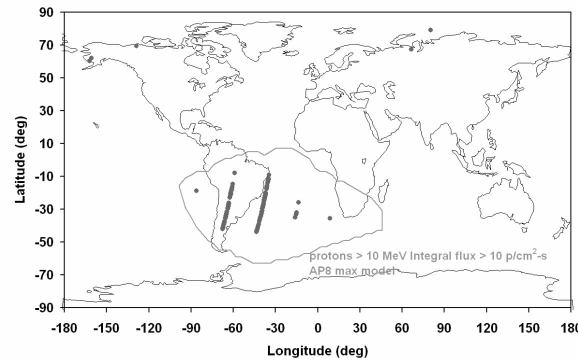

Fig. 4. Geographical location of the SEUs on July 13, 2000.

Fig. 5 shows the cartography of SEUs for a large SPE day, July 14, 2000. On this day the SEU count was 1188. About the same number of SEUs occurred within the SAA as on July 13, 2000, but the increased levels of protons and heavy ions from a solar event induced a larger number of SEUs in the high latitude regions of the orbit.

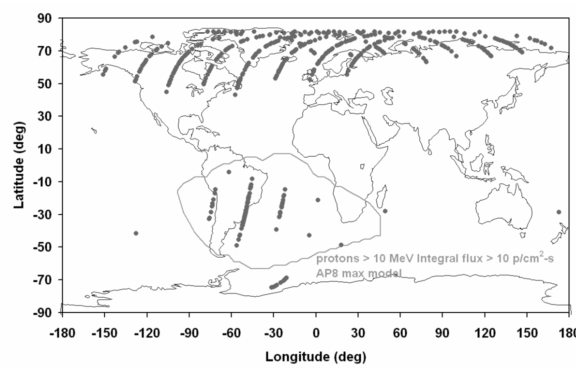

Fig. 5. Geographical location of SEUs on July 14, 2000.

About 20% of the telemetry files showing SEUs indicate that multiple upsets occurred during the 10 second telemetry gathering period. The probability of concurrent upsets from multiple particles occurring during such a short period of time is quasi negligible. Therefore, we may assume that these multiple events are due to a single particle. The flight data show that both protons and heavy ions can create these Multiple Event Upsets (MEUs). Most MEUs affect two or three memory cells. However, larger MEUs that could affect up to 30 memory cells were observed. These large multiple upsets were only observed in the high latitude regions of the spacecraft's orbit. Therefore, we assume that they were due to high Linear Energy Transfer (LET) cosmic rays or solar ions.

Large MEUs were observed on November 9, 2000, April 15, 2001, and November 5 and 6, 2001 SPEs. It is interesting to note that these are the SPEs with the strongest ion component.

IV. Comparison of Actual Rates to Predictions

The heavy ion ground test data were taken on the flight lot (date code 9147) [21]. Proton ground test data on lots other than the flight lot were found in the literature [5, 22]. Predictions were performed with CREME 96 [23] using a Weibull fit of test data and assuming a 4µm thickness of sensitive volume, and 100 mils Aluminum shielding thickness. Weibull fitting parameters of ground test data used for the predictions are presented in Table I.

TABLE I
Cross-Section Data Fitting Parameters
Used for the Predictions

Weibull fit parameters	Heavy-ion data	Proton data
Onset	1.7 MeVcm^2/mg	18 MeV
Width	5.0 MeVcm^2/mg	20 MeV
Power	1	1
Plateau	13 μm^2/bit	0.064 10^{-12} cm^2/bit

Solar minimum and solar maximum models were used for the background environment (AP8 [24] for trapped protons and CREME 96 for GCRs). For the SEU rates during a Solar Particle event, we used the CREME 96 worst day model. Results are shown in Table II.

TABLE II
Comparison of Actual SEU Rates with Predictions

Environment	Calculated SEU rates, both SSRs [SEU/day]	Actual SEU rates, both SSRs [SEU/day]
Background	938 (solar minimum)	255 (max monthly average)
	447 (solar maximum)	167 (min monthly average)
SPE	291,000 (worst-day)	~1000 (July 14, 2000)
		~400 (July 15, 2000)
		~1000 (November 9, 2000)
		~280 (April 15, 2001)
		~300 (November 5, 2001)
		~300 (November 6, 2001)

A. Background Environment

We can see in Table II that the calculated SEU rate using the solar minimum models overestimates the actual SEU rates due to the background environment by a factor 4 to 6. Using solar minimum conditions is considered as a worst-case approach because trapped proton fluxes and GCR fluxes are highest during solar minimum. On the other hand, solar maximum conditions are considered as a best case. And, as about 85% of the SEUs occur in the SAA, we expected an underestimation of the SEU rate, because the AP8 model underestimates the actual trapped protons fluxes at low altitude [25]. We can see in Table II that the calculated SEU rate with the solar maximum models overestimates the actual SEU rates by a factor 2 to 3. This overestimation may be due to different factors: conservative SEU characterization, conservative shielding assumptions, and conservative sensitive volume thickness assumptions. However, a factor 2 to 6 overestimation, depending on the solar condition considered, can be considered as a reasonable agreement. Because flight data were collected during solar maximum conditions, the solar maximum prediction gives a closer estimation of the actual flight SEU rates. For the solar maximum condition, the predicted proton induced SEUs to heavy ion induced SEUs ratio is 87%. It is close to the ratio observed on the flight data where about 85% of SEUs occur in SAA, and the remaining 15% are induced by GCRs (about 84% of GCRs are protons).

B. Solar Particle Event Environment

The predicted SPE rate overestimates the actual rates during the largest events by 2 to 3 orders of magnitude. SPEs are hugely variable in intensity, spectral hardness and composition. CREME 96 SPE worst day model gives a worst-case estimation of the Solar Particle fluxes based on the October 1989 SPE. The October 1989 event is one of the largest SPE ever observed; therefore, an overestimation was expected. However, such a large overestimation was not expected, because the largest SPEs that occurred during the observation period were equal in ion and proton levels to the CREME 96 worst day model [26]. Fig. 6 compares the CREME 96 worst day incident integral proton flux with the incident proton fluxes measured by GOES during the large SPEs of the current solar cycle. We can see that the largest SPEs of July 14, 2000, and November 9, 2000, are very close to the CREME 96 worst day model.

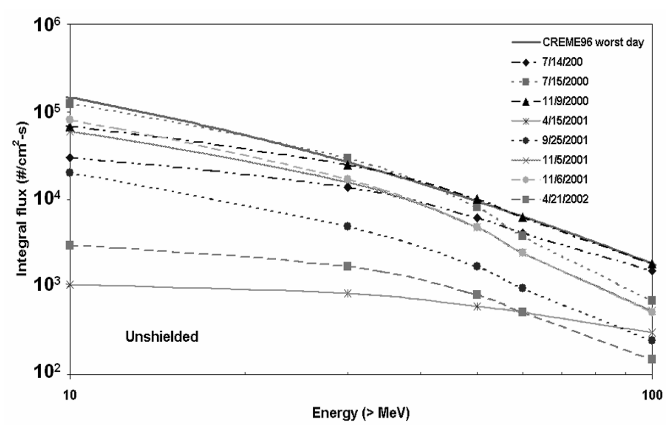

Fig. 6. Integral solar proton fluxes (daily averages) measured by GOES [20] during the largest solar events of the current solar cycle compared with the CREME 96 worst day model (GEO orbit, incident flux).

Fig. 7 compares the LET spectra of the worst day of the major SPEs of the current solar cycle with the CREME 96 model. We can see that at low LET (LET < 1MeVcm^2/mg)

July 14, 2000, and November 5, 2001 events are very close to the model. For LET > 1 MeVcm^2/mg, the April 15, 2001 event is close to the model.

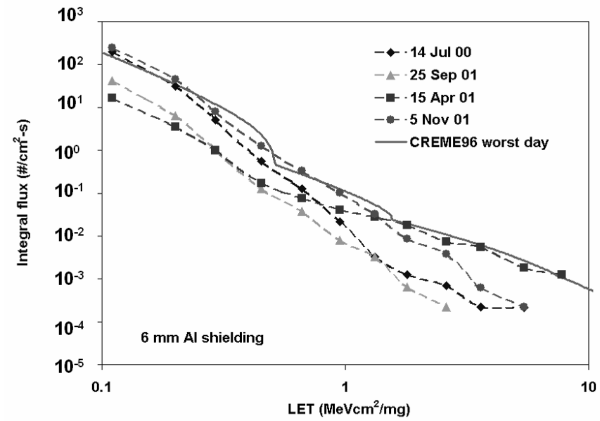

Fig. 7. Integral LET spectra measured with the CREDO3 instrument flying on MPTB [26] during the largest solar events of the current solar cycle compared with the CREME 96 worst day model (MPTB orbit, 236 mils of Al shielding).

If we look at Fig. 6, we can deduce that only the high-energy protons have an impact on the SEU numbers during SPEs. For example, the proton > 30 MeV and > 50 MeV fluxes are larger on July 15, 2000 than on July 14, 2000. However, the SEU count on July 14 is twice the SEU count on July 15. In September 2001 the proton > 60 MeV fluxes are significantly higher than the same fluxes on April 15, 2001, but the SEU count on April 15, 2001 is higher. Fig. 8 compares the SEU count increases during the largest SPEs with the > 100 MeV proton fluxes for these days. We can see the excellent correlation. As the DRAM proton energy threshold is about 20 MeV, this implies that a thicker shielding thickness surrounds the SSRs than the assumed 100 mils.

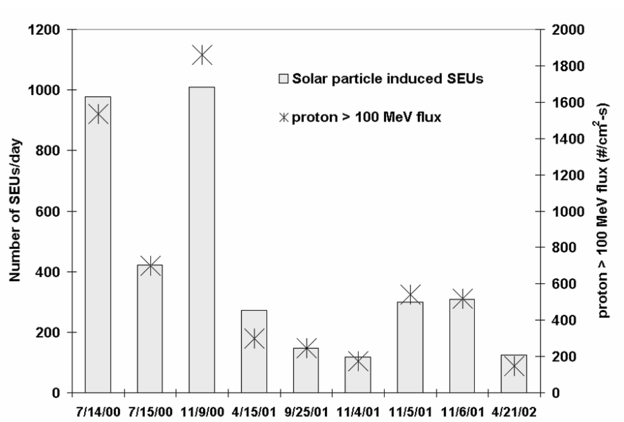

Fig. 8. Comparison of the SPE induced SEU counts to the > 100 MeV proton daily averages fluxes measured by GOES [20].

The predicted ratio of the proton induced SEU rate to heavy ion induced SEU rate is 9%. This does not correspond to the flight data results and also indicates a shielding assumption that is too conservative.

Solar particle energy spectra are softer than the background particle spectra (trapped protons and GCRs) [27]. Fig. 9 and Fig. 10 show the CREME 96 worst day solar proton energy spectra and heavy ion LET spectra respectively for different shielding thickness. We can see the significant effect of the shielding.

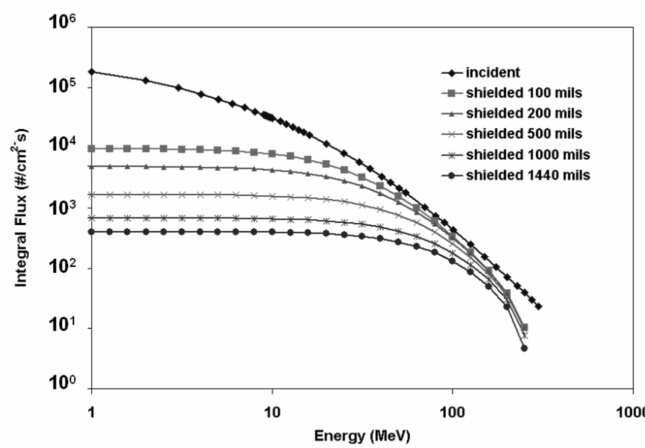

Fig. 9. CREME 96 worst day model proton spectra for different shielding thickness (Orbview-2 orbit).

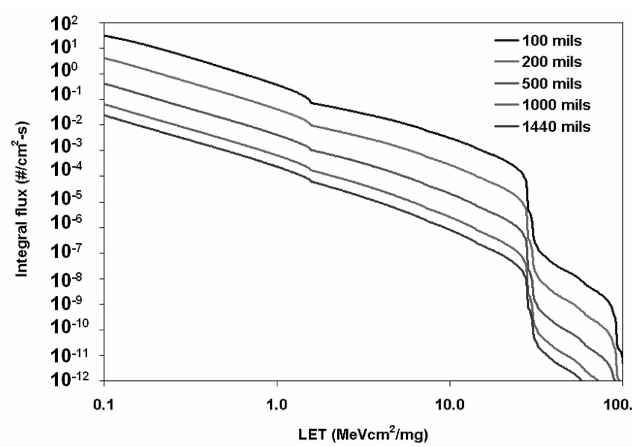

Fig. 10. CREME 96 worst day model heavy ion LET spectra for different shielding thickness (Orbview-2 orbit).

C. Recalculated SEU Rates

We have estimated that an “equivalent” shielding thickness of 1440 mils surrounds the DRAMs in the SSRs. Table III gives the calculated rates with this shielding thickness. The calculated SPE rate is reduced by 2 orders of magnitude and now overestimates the actual SPE rates by a factor of 3 to 10. Also, the ratio of the predicted proton induced SEU rate to the heavy ion induced SEU rate is now 95%.

The background environment predicted rates are also reduced by a factor of 2, and now the solar maximum prediction is very close to the actual SEU rates. Fig. 11 compares the calculated rates for the background environment using the updated shielding estimate with the actual monthly average rates. The ratio of the predicted SEU rate for solar maximum to the actual SEU rates varies from 0.9 to 1.4. In addition to the best case (solar maximum) and worst case (solar minimum) GCR flux models, CREME 96 provides a model of solar modulation of GCR fluxes. We have calculated the SEU rates for the beginning of each year from 1999 to 2003. The results are shown in Table III and Fig. 11. The predicted rate for the beginning of 1999 is 333 SEU/day, and the predicted rate for the beginning of 2003 is 253 SEU/day. We can see that the modulated rates follow the trend of the actual data even though the decrease is lower because CREME 96 does not provide a modulation for the trapped proton fluxes.

TABLE III
CALCULATED RATES WITH A 1440 MILS AL SHIELDING THICKNESS

Environment	Calculated SEU rates, both SSRs [SEU/day]
Background	414 (solar minimum)
	238 (solar maximum)
	333 (1999.0)
	328 (2000.0)
	307 (2001.0)
	271 (2002.0)
	253 (2003.0)
SPE	2760 (worst day)

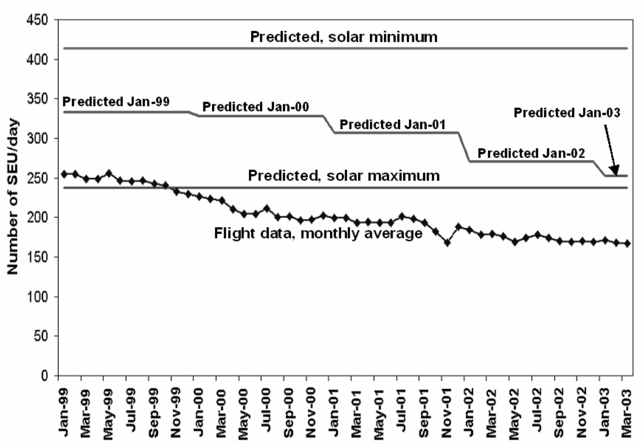

Fig. 11. Predicted and actual SEU rates induced by the background environment, 1440 mils of Al shielding.

V. PERFORMANCE OF THE SEE MITIGATION METHOD

Flight data show that about 20% of the events are MEUs. These MEUs occur in functionally different data structures because of the SSR memory devices' one bit organization. Therefore, these MEUs do not have any impact on the EDAC performances.

The EDAC Hamming code will fail if the same data structure is hit in two separate devices due to coincidental but independent events. This probability is kept small if the memory is scrubbed at a sufficiently rapid rate. In this kind of orbit, it is not good statistics to calculate the probability of failure on the basis of daily averaged SEU rates. We have seen that the large majority of SEUs, about 85%, occur only within the SAA in bursts lasting less than 20 minutes for each orbit. Thus, the trapped protons give a very high SEU rate that increases the probability of failure. Fig. 12 shows the probability of failure versus the scrubbing period. We have calculated a probability of failure for a 5-year mission based on the peak rates observed within the SAA and on the orbit averaged rates [28]. The probability to have one EDAC failure during a 5-year mission is about 0.2 based on the peak rates for the 16 minutes scrubbing period. We can see in Fig. 12 that the probability of failure based on the orbit averaged rates is one order of magnitude lower. We have also calculated the probability of failure during a large solar event day and observed that this probability is negligible. These calculations are consistent with the in flight observations where no science data were lost.

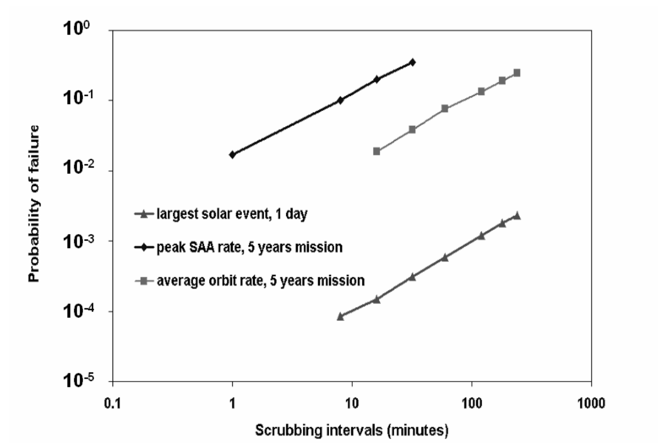

Fig. 12. Probability of failure versus scrubbing interval.

VI. CONCLUSION

Long term observations of flight data, like those presented here, allow the correlation between the variations in the space environment and the system effects. From day to day, the SEU rates can vary significantly (several orders of magnitude). The predicted rates give an acceptable idea of the actual average rate due to the background environment but do not represent the day-to-day fluctuations and the long-term modulation with the solar activity. Predictions should take into account this solar modulation. The SEU count increases significantly during SPEs. SPE predictions may overestimate significantly the actual SPE rates if conservative shielding assumptions are made. Therefore, realistic shielding models are required for solar event rate predictions.

Hamming EDAC show their efficiency to mitigate SEU in SSR applications as long as MEUs induced by single particles do not create multiple errors in an SSR data word, and the scrubbing rate is sufficient. The data show that about 85% of the SEUs occur within the SAA in bursts lasting less than 20 minutes per orbit. During SPEs, the SEU rates may also be high outside the SAA; therefore, it is important to calculate the scrubbing rate for these peak SEU rates. It should also be noted that the simple EDAC schemes might not be as effective for more modern memory devices that have more complex error modes.

VII. Acknowledgment

The authors thank Orbital Sciences Corp. for providing the SSR data and Clive Dyer for providing the CREDO data.

VIII. References

[1] C.M. Seidleck, K. A. LaBel, A. K. Moran, M. Gates, J. L. Barth, E. G. Stassinopoulos, and T. D. Gruner, "Single Event Effect Flight Data Analysis of Multiple NASA Spacecraft and Experiments; Implications to Spacecraft Electrical Designs," RADECS 1995 Proceedings, pp. 581-588, 1996.

[2] C.I. Underwood, "The Single-Event-Effect Behavior of Commercial-Off-The-Shelf Memory Devices-A Decade in Low-Earth Orbit," RADECS 1997 Proceedings, pp. 251-258, 1998.

[3] C.I. Underwood, and M. K. Oldfield, "Observed Radiation-Induced Degradation of Commercial-Off-The Shelf (COTS) Devices Operating in Low-Earth Orbit," *IEEE Trans. on Nuc. Sci*., vol. 45, no. 6, pp. 2737-2744, Dec. 1998.

[4] C.I. Underwood, and M. K. Oldfield, "Observations on the Reliability of COTS-Device-Based Solid State Data Recorders Operating in Low Earth Orbit," RADECS 1999 Proceedings, pp. 387-393, 2000.

[5] E.G. Mullen, K. P. Ray, R. Koga, E. G. Holeman, and D. E. Delorey, "SEU Results from the Advanced Photovoltaic and Electronics Experiments (APEX) Satellite," *IEEE Trans. on Nuc. Sci.*, vol. 42, no. 6, pp. 1988-1994, Dec. 1995.

[6] R. Harboe-Sorensen, E. Daly, F. Teston, H. Schweitzer, R. Nartallo, P. Perol, F. Vandenbussche, H. Dzitko, and J. Cretolle, "Observation and Analysis of Single Event Effects On-board the SOHO Satellite," RADECS 2001 proceedings, 2001.

[7] T. Goka, H. Matsumoto, and N. Nemoto, "SEE Flight Data from Japanese Satellites," *IEEE Trans. on Nuc. Sci.*, vol. 45, no. 6, pp. 2771-2778, Dec. 1998.

[8] R. Ecoffet, M. Prieur, M. F. Del Castillo, S. Duzellier, and D. Falguere, "Influence of Solar Cycle on SPOT1-2-3 Upset Rates," *IEEE Trans. on Nuc. Sci.*, vol. 42, no. 6, pp. 1983-1987, Dec. 1995.

[9] J.L. Barth, J. W. Adolphsen, and G. B. Gee, "Single Event Effects on Commercial SRAMs and Power MOSFETs: Final Results of the CRUX Flight Experiment on APEX," 1998 IEEE Radiation Effects Data Workshop proceedings, pp 1-10, 1998.

[10] S. Duzellier, D. Falguere, R. Ecoffet, and I. Tsourilo, "EXEQ II et III: Experiences embarquées pour l'étude des événement singuliers," RADECS 1997 Proceedings, pp. 504-509, 1998.

[11] D. Falguere, S. Duzellier, R. Ecoffet, and I. Tsourilo, "EXEQ I-IV: SEE In-Flight Measurement on the MIR Orbital Station," 2000 IEEE Radiation Effects Data Workshop proceedings, pp 89-95, 2000.

[12] S. Duzellier, S. Bourdarie, R. Velazco, B. Nicholescu, and R. Ecoffet, "SEE In-Flight Data for two Static 32KB Memories on High Earth Orbit," 2002 IEEE Radiation Effects Data Workshop, pp. 1-6, 2002.

[13] S. Buchner, A. B. Campbell, T. Meehan, K. A. Clark, D. McMorrow, C. Dyer, C. Sanderson, C. Comber, and S. Kuboyama, "Investigation of Single-Ion Multiple-Bit Upsets in Memories on Board a Space Experiment," RADECS 1999 Proceedings, pp. 558-564, 2000.

[14] A. Campbell, S. Buchner, E. Petersen, B. Blake, J. Mazur, and C. Dyer, "SEU Measurement and Predictions on MPTB for a Large Energetic Solar Particle Event," RADECS 2001 Proceedings.

[15] J. Barak, J. L. Barth, C. M. Seidleck, C. J. Marshall, P. W. Marshall, M. A. Carts, and R. A. Reed, "Single Event Upsets in the Dual-Port-Board SRAMs of the MPTB Experiment," RADECS 1999 Proceedings, pp. 582-587, 2000.

[16] D. Falguere, D. Boscher, T. Nuns, S. Duzellier, S. Bourdarie, R. Ecoffet, S. Barde, J. Cueto, C. Alonzo, and C. Hoffman, "In-Flight Observations of the Radiative Environment and its Effects on Devices in the SAC-C Polar Orbit," *IEEE Trans. on Nuc. Sci.*, vol. 49, no. 6, pp. 2782-2787, Dec. 2002.

[17] G.M. Swift, and S. M. Guertin, "In Flight Observations of Multiple Bit Upset in DRAMs," *IEEE Trans. on Nuc. Sci.*, vol. 47, no. 6, pp. 2386-2391, Dec. 2000.

[18] K.A. LaBel, P. W. Marshall, J. L. Barth, R. B. Katz, R. A. Reed, H. W. Leideker, H. S. Kim, and C. J. Marshall "Investigation of an in flight anomaly: Investigation of Proton SEE Test Results for Stacked IBM DRAMs," ," *IEEE Trans. on Nuc. Sci*., vol. 45, no. 6, pp. 2898-2903, Dec. 1998.

[19] Sunspot and Space Weather information pages, Solar Influences Data analysis Center (SIDC) archives, http://sidc.oma.be

[20] NOAA Space Physics Interactive Data Resource (SPIDR) archives, http://spidr.ngdc.noaa.gov

[21] "DRAM Single Event Effects and Total Ionizing Dose Test Results," Rockwell test report, Apr. 1992.

[22] R. Harboe Sorensen, "Proton SEE results – A Summary of ESA's Ground Test Data ," RADECS 1997 Data Workshop proceedings, pp. 89-96, 1997.

[23] A.J. Tylka, J.H. Adams, P.R. Boberg, W.F. Dietrich, E. O. Flueckiger, E. L. Petersen, M. A. Shea, D. F. Smart, and E. C. Smith, "CREME 96: A Revision of the Cosmic Ray Effects on Micro-electronics Code," *IEEE Trans. on Nuc. Sci.*, vol. 44, no. 6, pp. 2150-2160, Dec. 1997.

[24] D. M. Sawyer and J. I. Vette, "AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum," NSSDC/WDC-A-R&S, 76-06, NASA/Goddard Space Flight Center, Greenbelt, MD, Dec. 1976.

[25] E. J. Daly, J. Lemaire, D. Heynderickx, and D. J. Rodgers, "Problems with Models of the Radiation Belts," *IEEE Trans. on Nuc. Sci*. vol. 43, no. 2, pp. 403-415, Apr. 1996.

[26] C.S. Dyer, K. Hunter, S. Clucas, D. Rodgers, A. Campbell, S. Buchner, "Observation of Solar Particle Events from CREDO and MPTB During the Current Solar Maximum," *IEEE Trans. on Nuc. Sci*., vol. 49, no. 6, pp. 2771-2775, Dec. 2002.

[27] E. C. Smith, "Effects of Realistic Shielding on SEE Rates," *IEEE Trans. on Nuc. Sci*., vol. 41, no. 6, pp. 2396-2399, Dec. 1994.

[28] D. Peyre, "Calculation of the probability of un-correctable errors due to SEU accumulation for memories without protections, with (SEC-DED) EDAC, and with (SEC-DED) EDAC plus scrubbing protection," Private communication, 2002.